LBL-35252

A Contrast-Based Scalefactor for Luminance Display

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Global illumination methods allow us to calculate physical values such as radiance and luminance at each pixel, but they do not tell us how to display these values. If we attempt to fully reproduce the world luminance levels on a computer monitor, slide or print, the results are usually disappointing, for a couple of reasons. First, contemporary display media fall short of the real world's dynamic range by a few orders of magnitude. It isn't possible to reproduce the luminances in bright and dark regions accurately. Second, the "adaptation luminance," or light level to which the viewer is accustomed, is almost always different under the real world and computer display viewing conditions, and this affects visual response dramatically.

A common solution to this problem is that of an automatic exposure camera: determine the average luminance value on the image and compute a scalefactor that takes this level to a reasonable value for display, perhaps one half the maximum display brightness (ie. input=0.5)*. This solution has the effect of making visible on the display, values that are close to the average world luminance in the image. Values much higher or lower are clipped to the maximum and minimum display values, respectively. Bright areas appear as white and dark areas appear as black. Figure 1a shows a simulation of a daylit cabin space. A scalefactor for the display values was computed from a logarithmic average of the image luminance at each pixel. Figure 1b shows a simulation of the same cabin space at night with electric lighting. Since we are scaling the nighttime image to the same average display value as the daytime scene, the second image does not properly convey that there is in fact less light and decreased visibility under nighttime conditions.

An early attempt to induce appropriate viewer responses from a CRT display was put forth by Miller, Ngai and Miller [Miller84]. Their method was based on the brightness sensitivity work of Stevens and Stevens [Stevens63], and its explicit goal was to reproduce equivalent brightness ratios on the CRT as would be present in the real world†. Thus, if a given object looks twice as bright as another in the real world, they wanted it to look twice as bright on the display. Although this seems logical, the eye is much more attuned to contrast than it is to brightness, so mapping brightness ratios independent of contrast does little to represent how well a person is actually able to "see" in an

*In this article, we assume that monitor gamma response and other such non-linear effects have been corrected, so we have a linear relationship between input pixel value and output display luminance. We further assume that the minimum display luminance corresponds to an input of 0 and the maximum luminance corresponds to an input of 1.

†Brightness is defined as the psychophysiological response to light stimulus, as opposed to luminance, which is a physical quantity that can be more easily measured.

environment. Figure 2a and 2b show the day versus night example given previously, using Miller's function adjusted for book printing rather than CRT display*. The difference between the images is slight, and in general we have not found this to be a very useful brightness mapping for judging lighting quality.

Perhaps the best treatment of the display problem to date is that of Jack Tumblin and Holly Rushmeier [Tumblin91]. Using the brightness mapping function they developed, bright scenes will show good visibility (ie. high contrast), and dark scenes will show poor visibility (ie. low contrast). Figures 3a and 3b show the Tumblin-Rushmeier formula applied to our previous simulation. Notice that the contrast is slightly lower than the average exposure in the nighttime case, and overall it is a little darker. In the daytime image (3a), the Tumblin-Rushmeier mapping works out to:

$$input = 0.00427\, L^{1.04}$$

In the nighttime image (3b), the Tumblin-Rushmeier mapping works out to:

$$input = 0.221\, L^{0.747}$$

The coefficients and exponents in these formulas were determined by the world adaptation luminance taken from the log averages, 29.6 candelas/meter^2 for daytime and 0.567 cd/m^2 for nighttime. (A candela is a lumen per steradian, and lumens are related to watts by the photopic sensitivity curve, $v(\lambda)$ [Wyszecki82].) The original pixel value, L, is expressed in cd/m^2†. We must emphasize that the above mapping parameters are peculiar to this scene and these two lighting conditions, and the coefficients and powers shown here would be different under other conditions. In general, darker scenes have lower powers (reducing contrast), and brighter scenes have higher powers (increasing contrast). The reader should refer to the original technical report to learn how these values are derived.

The Tumblin-Rushmeier brightness mapping attacks the adaptation problem with a non-linear formulation based on contrast. Rather than attempt to improve on their formula by adding terms, we want to derive a simpler, linear function that has some of the same advantages. A linear function also has the potential advantage of representing a darker scene with a darker display, which may be more natural than a display with a similar mean value but reduced contrast.

Derivation

Our goal is simple: find a constant of proportionality between display luminance and world luminance that yields a display with roughly the same *contrast visibility* as the actual scene. We base our scalefactor on the subject studies conducted in the early 1970's by Blackwell [CIE81]. Using a briefly flashed dot on a uniform background,

*Note that book printing introduces another source of error, and our assumptions about reader viewing conditions (500 lux illumination) and the printing process (75% maximum reflectance) are only best guesses.

†We separated color information to reduce color shifts, though this is probably not the best approach. Very little conclusive work has been published on color adaptation, and this seems to be a ripe area for new research.

Blackwell established the following relationship between adaptation luminance (L_a) and minimum discernible difference in luminance:

$$\Delta L(L_a) = 0.0594\,(1.219 + L_a^{0.4})^{2.5}$$

(Luminances in this formula are expressed in SI units of cd/m^2.) This formula tells us what is visible at a given luminance level. That is, $L_a \pm \Delta L$ is discernible on a background of L_a, but $L_a \pm \varepsilon$ for $\varepsilon < \Delta L$ is not. We can exploit this relationship simply by linking display adaptation and visibility to world adaptation and visibility.

We want a linear formula, so we seek a multiplier m such that:

$$L_d = m\,L_w$$

where:

L_d = display luminance at an image point
L_w = world luminance at an image point

Thus, the displayed image will be some factor more or less luminous than the real scene. The contrast visibility can be made the same simply because a darker display has reduced contrast visibility and a brighter display has increased contrast visibility.

Using $\Delta L(L_a)$, we can correlate visible luminance differences on the display to luminance differences in the scene:

$$\Delta L(L_{da}) = m\,\Delta L(L_{wa})$$

where:

$\Delta L(L_{da})$ = minimum discernible luminance change at L_{da}
L_{da} = display adaptation luminance
L_{wa} = world adaptation luminance

This equation is really the key assumption that allows us to calculate m, so let's try to understand what it means. On the left side, we have $\Delta L(L_{da})$, which is the minimum visible luminance difference at the display adaptation level. On the right side, we have $m\,\Delta L(L_{wa})$, which is our multiplier, m, times the minimum visible luminance difference at the world adaptation level. That is, when we apply our multiplier to the calculated luminance values and display the result, the differences that are just visible in the real world should be just visible on our display. Solving for m, we arrive at our multiplier:

$$m = \left[\frac{1.219 + L_{da}^{0.4}}{1.219 + L_{wa}^{0.4}}\right]^{2.5}$$

Remember that this multiplier converts from world luminance to display luminance. To get a scalefactor that computes display input in the range 0 to 1, we need to know the maximum display luminance, L_{dmax}*. We also need to know the display adaptation luminance of the viewer, L_{da}. Assuming nominal viewing conditions, ie. the display is in

*For simplicity, we assume that the minimum display luminance is zero. As long as it is small in relation to the maximum value, it has little effect on visible contrast and is therefore a minor consideration.

surroundings that are not very much brighter or darker than the display itself, we can relate adaptation luminance to maximum display luminance. We have found that $L_{da} = L_{dmax}/2$ is close enough for most applications. The final scalefactor to get from world luminance to display input is then:

$$sf = \frac{1}{L_{dmax}} \left[\frac{1.219 + (L_{dmax}/2)^{0.4}}{1.219 + L_{wa}^{0.4}} \right]^{2.5}$$

The two unknowns in the equation are the maximum display luminance, L_{dmax}, and the world adaptation luminance, L_{wa}. The maximum display luminance can be measured with a luminance meter. A typical value for a modern color CRT display is 100 cd/m^2. Under good indoor lighting, a photograph has a maximum luminance close to this value at around 120 cd/m^2. The world adaptation level can be determined a couple of ways. One way is to take a log average of the image as was done by Tumblin and Rushmeier, possibly excluding light sources not in direct line of sight. This approach assumes that since we cannot determine the true viewer adaptation, which changes as a function of fixation, a global average is the best guess. Another approach is to assume that an imaginary person in the scene has fixated on a certain point, and use that area of the image to set the adaptation level. We can then interpret the result as telling us how well a person would see in an environment while looking at this point.

Results

Figure 4a shows our daylit scene with a scalefactor of 0.0145 computed from a log average approximation of the world adaptation luminance. Figure 4b shows our nighttime scene with its corresponding scalefactor of 0.147. Since the computed luminances in 4b were much smaller than under daylight conditions, the final image is darker despite the larger scalefactor.

Because our scalefactors were derived from contrast visibility predictions, we can argue that these two figures give a reasonable impression of how well a person could see under the two lighting conditions. Furthermore, it is obvious which scene is darker.

Continuing our exploration of contrast visibility, we may produce images using a local viewer adaptation instead of a global adaptation. For example, let's say a person is only looking at the cabin window, and is adapted to the luminance of that local area. Under daylight conditions, that would mean an adaptation luminance of about 918 cd/m^2. We calculate a corresponding scalefactor of 0.000765, which produces Figure 5a. Note that we can now see what is outside the window quite clearly, though our new adaptation means we cannot see the interior as well. However, when we adjust our adaptation in the nighttime scene for looking at the cabin window (L_{wa} = 0.34 cd/m^2, sf = 0.457), the resulting image (Figure 5b) shows little local improvement in visibility. This tells us that we cannot see such darker areas at this low light level.

Figure 6a shows the lower deck of a naval vessel under standard lighting conditions. Figure 6b shows the same deck under emergency lighting conditions. Scalefactors were computed from a linear average of non-source luminances, which we think is the more appropriate for scenes with small light sources. Images like these and walk-through animations have been used to evaluate alternatives for shipboard lighting. Without some tie to visibility, there would be no basis for such comparisons.

Conclusion

We have presented the calculation of a linear scalefactor for display of global illumination results. The calculation is based on contrast sensitivity studies conducted by Blackwell the early 1970's. The result is a display that represents visibility under known lighting and viewing conditions, showing bright lighting as a bright display and dark lighting conditions as a dark display. It is easy to dismiss this as too obvious, but the scalefactor is not the same for all scenes; it adjusts to maintain the same visibility level on the display as would be present in the real world. Thus, the subjective reaction of the viewer under real and simulated conditions should be similar, and the display is that much more meaningful. If an object is discernible on the display, then it would be discernible in the actual space. If it is too dark to see on the display, then it would be too dark to see in real life.

We wish to emphasize that our approach is not inherently superior to other approaches. In fact, it uses a much simpler viewer model than that of Tumblin and Rushmeier. The main advantage is the convenience of a global linear scalefactor, which preserves color and image contrast, making dark scenes really appear dark.

Related Work

Early investigation of subjective image processing was done by Thomas Stockham [Stockham72], who recommended (among other things) a logarithmic pixel encoding to preserve dynamic range.

Interested readers should also look up Chiu, Herf, Shirley, Swamy, Wang and Zimmerman's recent paper on spatially nonuniform brightness mappings [Chiu93]. Their paper addresses some of the problems in representing images with wide dynamic ranges, and offers an interesting solution.

The Radiance Synthetic Imaging System was used to render and process the images presented in this article. This software is available from anonymous ftp at hobbes.lbl.gov (128.3.12.38). This type of image processing almost demands a floating point image format. Such a format is used in Radiance, and described in [Ward91].

Acknowledgements

Robert Clear provided much of the background that led to this formulation, which was inspired by some comments from Sam Berman. Thanks also to Jack Tumblin and Holly Rushmeier, who helped us to understand and apply their mapping function. Cindy Larson created the cabin model. Saba Rofchaei developed much of the ship model, which was funded under contract N6153392F0854 by the U.S. Department of Navy, D.W. Taylor Naval R & D Center, to improve energy-efficiency of shipboard lighting. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Buildings Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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